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Confronting potential future augmentations of the physiologically equivalent temperature through public space design: The case of Rossio, Lisbon

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ABSTRACT

When considering cities such as Lisbon, which due to their Köppen Geiger classification of '*Csa*', witness hot and dry summers, the translation of local bottom-up knowhow upon climatic guidelines has been a topic of considerable dissemination over recent years.

Depicting upon a concrete case study located in Lisbon's historical quarter, the results from a previous bioclimatic study undertaken by the authors were taken further in order to consider how worst-case-scenarios of climate change (A1FI/RCP8.5) could potentially impact the existing human thermal environment within the square. In addition to considering its existing layout, public space design interventions were also examined within different thermal/temporal scenarios through the use the Physiologically Equivalent Temperature (PET) and PET(Load) indices.

The results of the study revealed that within a climatic worse-case-scenario, and without any adaptive measures to address Physiological Stress (PS) levels, the majority of the square presented potential PS thresholds ranging between 'Extreme Heat Stress Lv.3/4', with PET values exceeding that of 51 °C and 56 °C. On the other hand, and particularly in regions prone to high levels of solar radiation, the thermal amelioration effects of the proposed public space design interventions presented reductions of PET values up to 16.6 °C.

1. Introduction

Recently, several agendas have presented themselves upon the contemporary and interdisciplinary practice of urban planning and design. Engrained within such agendas, lies the comprehension of how climate change adaptation can overcome issues of uncertainty and ambiguity until the end of the century. So far however, a considerable amount of research relating to 'locality' has been carried out through a top-down approach (Nouri, 2013). Such methods concentrate upon impact prediction through global models as a starting point to anticipate climate change scenarios. As a result, there has been a growing interest in bottom-up approaches that question how efforts at adaptation can be locally initiated and adopted (e.g., Wilbanks and Kates, 1999; Ali-Toudert and Mayer, 2007; Algeciras, Consuegra, & Matzarakis, 2016; Gómez, Cueva, Valcuende, & Matzarakis, 2013; Lin, Matzarakis, & Hwang, 2010; Mayer and Höppe, 1987; Nikolopoulou, 2007; Nouri and Costa, 2017a; Oliveira, Andrade, & Vaz, 2011; Shashua-Bar, Tsiros, & Hoffman, 2012).

In accordance with Global Circulation Models, it has been identified so far that global temperature will likely continue to rise throughout the 21st century, and that there shall be significant changes to air humidity, wind speed and cloud cover around the planet. Conversely, the reports of the Intergovernmental Panel on Climate Change have often described the effect of weather with a simple index based on amalgamations of air temperature and relative humidity. Although it is clear that such descriptions have substantially propelled the maturing top-down climate change adaptation agenda, when considering bottom-up approaches to climatic vulnerability, the exclusion of vital meteorological factors (i.e. radiation fluxes, wind speed and human thermophysiological factors) have arguably diminished the significance of such results for local design and decision making (Matzarakis and Amelung, 2008; Matzarakis and Endler, 2010).

Abbreviations: PET, Physiologically Equivalent Temperature; POI, Point of Interest; PS, Physiological Stress; SRES, Special Report on Emission Scenarios; RCP, Representative Concentration Pathways; C, Cycle; PET, Physiologically Equivalent Temperature Load

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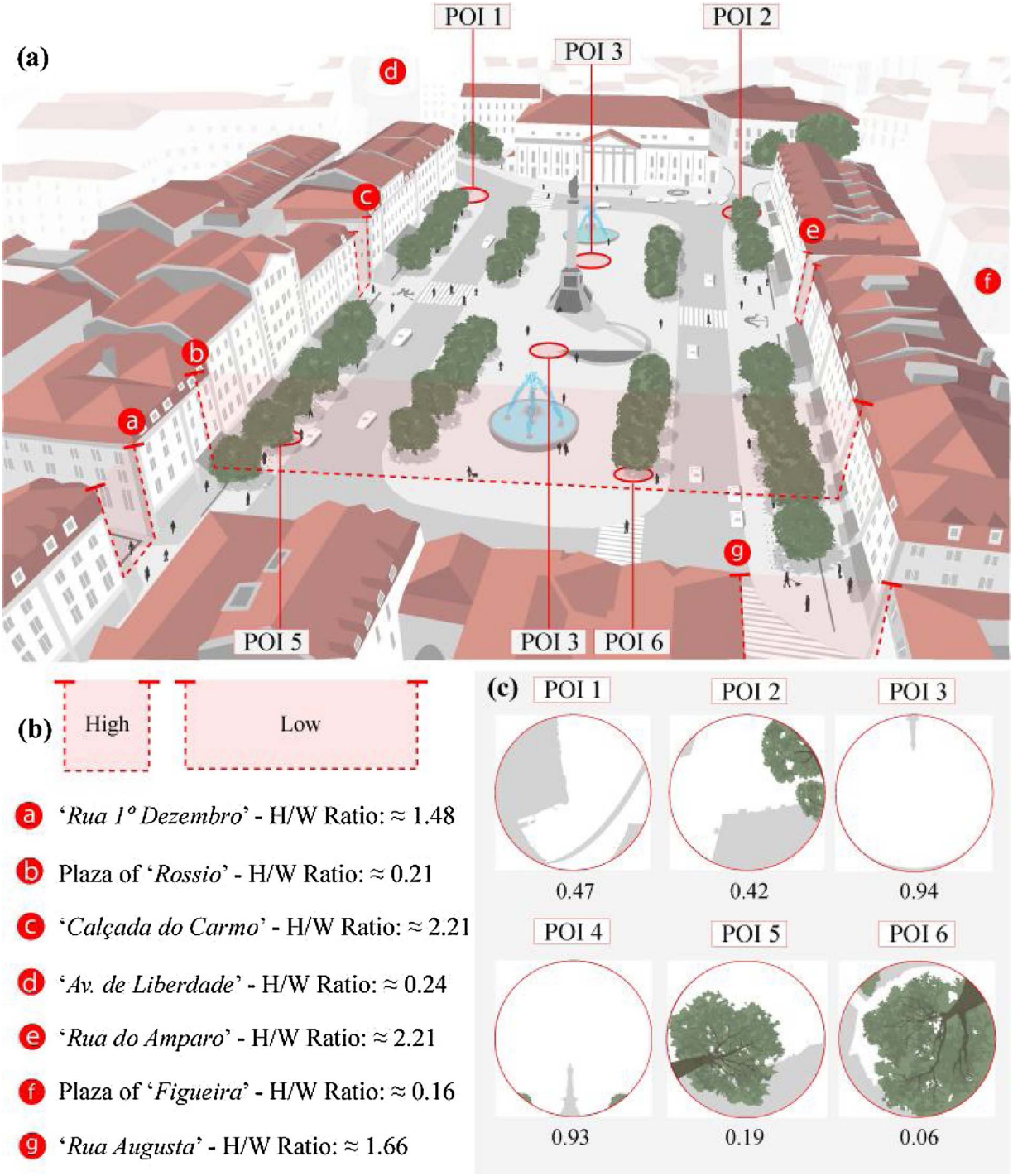


Fig. 1. (**a**) Southern perspective view of Rossio and location of each Point of Interest (POI) around the square | (**b**) Height-to-Width Ratios of Rossio, and surrounding canyons | (**c**) Polar diagrams for each POI, which were obtained through the use of a fish-eye lens camera and posteriorly simplified into vectorised before being processed by the Rayman.

The reason for such lapses can be attributed to the lack of climatic variables such as short and long wave radiation which are often not available in climate records. Nevertheless, and by referring to the methodology developed by Matzarakis and Amelung (2008), it is suggested that such gaps in climatic variables can be overcome. More specifically, and by referring to climatological and astronomical data to estimate short and long wave radiation fluxes, synoptic evaluations of climate change effects upon the thermal environment can be achieved. Thus, this approach enables existing biometeorological exemplary results to be explored within a future context, which in this article, focuses upon the potential bioclimatic environment by the end of the twenty-first century in Rossio.

Based upon this disclosed interest, this article further examines the results obtained from a previous climatic study by Nouri and Costa (2017b) that was undertaken in Rossio − Lisbon during the summer of 2015. In the initial study, the objectives were to: (i) identify the microclimatic risk factors within the different areas of the square; and, (ii) suggest conceptual solutions that could potentially improve outdoor thermal comfort during periods of annual accentuated climatological stress.

Considering the specific case of Lisbon, it has been identified that steps need to be taken to adapt to future climatic conditions that are

already being felt within urban contexts (Alcoforado and Matzarakis, 2010; Alcoforado, Lopes, Alves, & Canário, 2014). Since the 1980's, studies of Lisbon's urban climate have been disseminated in order to better inform the cohesion between the interdisciplinary spheres of urban planning/design with that of climatology and biometeorology. Thus far, such studies have focused upon general bioclimatic conditions within the public realm (e.g., Andrade, 2003; Oliveira and Andrade, 2007), effects and intensities of UHI's (e.g., Alcoforado and Andrade, 2006; Alcoforado et al., 2014; Lopes, Alves, Alcoforado, & Machete, 2013), wind studies (e.g., Alcoforado, Lopes, Andrade, Vasconcelos, & Vieira, 2006; Lopes, 2003), and, the integration with planning policy (e.g., Alcoforado, Lopes, Andrade, & Vasconcelos, 2005; Alcoforado and Matzarakis, 2010). Furthermore, and intrinsic to the developing climate change adaptation agenda, studies relating to potential future climate change impacts upon the urban realm have also been disseminated (e.g., Alcoforado, Andrade, & Oliveira, 2009; Costa, 2013; Costa, et al., 2013; Matos Silva, 2016; Matos Silva and Costa, 2017).

Invigorated by such studies, and although recognised that climate change and uncertainty go hand in hand, this article suggests that climate change adaptation should not be considered a 'vague concept' (Bourdin, 2010). Inversely, and as identified by Costa (2011), the concrete bond with specific localities is what substantiates such preciseness. As deliberated by Costa et al. (2013), it is here where the use of the 'What if?' agenda can provide means to: (i) estimate potential local climatic territorial impacts within a specific scenario; and just as importantly, (ii) anticipate potential resolutions and prospective alternatives as a response to the aforementioned assessments.

Within this study, and with the aim of considering opportunities for contemporary public space design, the following investigative question was launched: *If the A1FI (or RCP 8.5) scenario came to fruition, what impacts could this have upon the local biometeorological environment in Rossio?* In order to answer this question, and based upon use of the thermophysiological index, the Physiologically Equivalent Temperature (PET) (Höppe, 1999) was used to: (i) identify microclimatic risk factors that could be potentially aggravated by climate change impacts; and, (ii) scrutinise how the suggested conceptual solutions preform in attenuating such identified aggravations by the end of century.

2. Method

2.1. Site and existing bioclimatic conditions

The utilised biometeorological data within this study was obtained from a preceding assessment that was conducted by the authors within the historical quarter of downtown Lisbon, within the civic space of Rossio during the summer of 2015 (Nouri and Costa, 2017b). Through the use of Computational Fluid Dynamic and Shadow Behaviour Stimulation studies, six Points of Interest (POI) were established (Fig. 1**a**). The simulation of these two characteristics were based around establishing an initial understanding of wind patterns and radiation fluxes that has proven to be: (i) those most influenced by morphological and physical properties of the urban environment (Matzarakis, Fröhlich, & Gangwisch, 2016); (ii) proven to be the predominant parameters for thermal comfort studies (e.g., Algeciras et al., 2016; Lin, 2009; Lin et al., 2010; Walton, Dravitzki, & Donn, 2007); and, (iii) often disregarded in top-down climatic assessments (Matzarakis and Amelung, 2008). Such morphological considerations were particularly relevant, as within the historical district, most canyons present a relatively high H/W ratios (i.e., of ≈ 1.66), whereby in the case of Rossio, this ratio is considerably lower (i.e., of ≈ 0.21) (Fig. 1**b**), thus considerably raising its susceptibility to such microclimatic characteristics (Ketterer and Matzarakis, 2014).

The concept of establishing POI's was inspired by studies which analysed microclimatic patterns within pre-determined and concrete positions in an outdoor site/s (e.g., Alcoforado et al., 2014; Charalampopoulos, Tsiros, Chronopoulou-Sereli, & Matzarakis, 2016; Eliasson, Knez, Westerberg, Thorsson, & Lindberg, 2007; Nikolopoulou and Lykoudis, 2006; Picot, 2004; Shashua-Bar and Hoffman, 2000; Tsiros, 2010; Takács, Kiss, Hof, Tanács, & Kántor, 2016).

Within the previous study, five different types of meteorological measurements were undertaken within the study: Wind speed (V), ambient temperature (T_{amb}), relative humidity (RH), global radiation (G_{rad}), and surface temperature (T_{surf}). Overall, a total of 6650 measurements were obtained amongst seven visits that were distributed out on every Monday and Friday in order to obtain an overall climatic assessment of July 2015 (■ see Appendix A). Furthermore, and in addition to the input of geographical coordinates and altitude, and similar to the methodology used in studies by (Alcoforado et al., 2005; Algeciras et al., 2016; Oliveira et al., 2011), polar diagrams were taken in each POI (Fig. 1**c**) in order to evaluate each respective Sky-View-Factor.

In order to determine the effects of the thermal environment upon pedestrians, the study referred to the energy balance of the human body within the urban environment. This enabled the analysis of how the human body perceived a combination of atmospheric elements through the use of a thermophysiological index, PET that was processed by the Rayman Pro model (Matzarakis and Rutz, 2006; Matzarakis, Rutz, & Mayer, 2007). Subsequently, and in order to establish the ranges of Physiological Stress (PS), the comparative chart by Matzarakis, Mayer, and Iziomon (1999) was utilised (Table1).

By correlating the mean processed PET values for All Days ($\overline{PET_{AD}}$) with the PS thresholds, the study demonstrated the diurnal amount of thermal stress upon the pedestrians at each location. As expected, it was revealed that $\overline{PET_{AD}}$ was higher in locations with less shade, as was the case of POI 3 and 4 during the hotter hours of the day. Based upon these results (■ see Appendix B), all locations which obtained at least a 'Strong' PS grade were selected to explore how public space design could attenuate such thermal stimuli in the hottest POIs (i.e., POI 2/3/4/5).

2.1.1. Solution proposals

Within the final section of the study, the authors identified conceptual solutions for each of the four hottest POIs in order to explore the attenuation of thermal comfort thresholds in each of the respective locations. Expressed as $\overline{PET_{D3}}$, and with the aim of considering the worst-case-scenario, the obtained PET from Day 3 (hottest day out of the seven site visits) was used in order to consider how potential public space design interventions could attenuate encircling microclimatic stimuli within each of the four hottest POIs. Thus, and based upon a bottom-up approach, the proposed solutions were based upon three types of measures, namely, vegetation, shelter canopies, and water/misting systems as presented in Fig. 2.

Such proposals follow the approaches used in similar bioclimate studies where the introduction of thermal sensitive interventions were also suggested and/or implemented in order to attenuate the amount of thermal stimuli upon pedestrians. Often, but not limited to, such

Table 1
Ranges of the thermal index Physiologically Equivalent Temperature (PET) for different grades of Thermal Perception and Physiological Stress on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo (according to Matzarakis, 1997).
Source: (Adapted from, Matzarakis et al., 1999)

PET	Thermal Perception	Physiological Stress
4 °C	Very Cold	Extreme Cold Stress
	Cold	Strong Cold Stress
8 °C	Cool	Moderate Cold Stress
13 °C	Slightly Cool	Slight Cold Stress
18 °C	Comfortable	No Thermal Stress
23 °C	Slightly Warm	Slight Heat Stress
29 °C	Warm	Moderate Heat Stress
35 °C	Hot	Strong Heat Stress
> 41 °C	Very Hot	Extreme Heat Stress

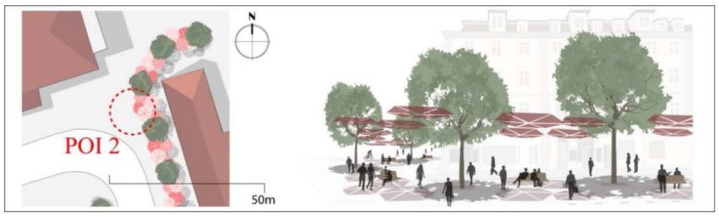
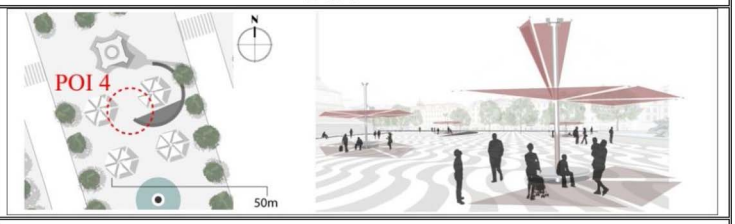
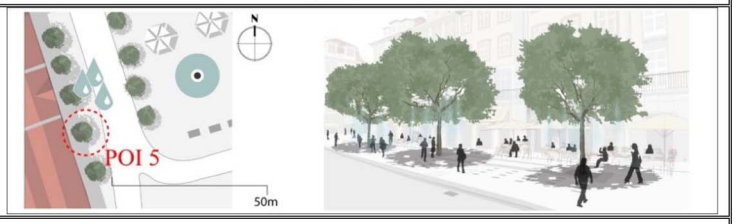
POI 2	
	
(*i*)	Existing linear plantation was extended by three trees (of the same species, i.e. *Tipuana Tipu*) in order to continue the vegetative shading upon the eastern sidewalk.
(*ii*)	Nylon canopies were suggested between the branches of the trees in order to induce a continuous shaded/seating area upon the middle of the pavement.
POI 3	
(*i*)	The introduction of a group plantation of six *Tipuana Tipu* trees was introduced in order to deflect accentuated amounts of radiation, and stronger wind currents.
(*ii*)	With a total area of 160m^2, a sheet of water would be sprayed through a micro nozzle system, which would subsequently be reabsorbed into the new paving slabs. To ensure that the desired RH levels were not exacerbated, the diurnal functioning period and water collection was fluctuated.
POI 4	
	
(*i*)	Based upon providing both seating and shading options for pedestrians. In order to augment perceived control between being cast in the sun or shade, four shelter canopies were suggested for the location which permitted each of the seven flaps to be independently.
POI 5	
	
(*i*)	Based upon a misting system which, unlike POI 2, would not allow surface wetting. The design of the system was based upon balancing T_{amb} and RH in order not to exacerbate atmospheric moisture content, and yet decrease air temperature. In order to quantify the balance between decreasing T_{amb} through the increase of RH levels, the ratio identified by Ishii, Tsujimoto et al. (2008) and Ishii, Tsujimoto et al. (2009) was used in order to propose an initial estimation on the correct amount of mist throughout the day.

Fig. 2. General descriptions of the conceptual public space design measures recommended for the hottest Points of Interest (POI) (Ishii et al. 2008, 2009).
Source: Author's figures (■ see Appendix C)

proposals occur in cities with '*Csa*' climates, which due to their hot and dry summers, particularly demand the presence of urban thermal sensitive interventions. With regards to vegetation, even at a meso/regional scale, Qiu et al. (2013) presented a summary of scientific studies that observed the cooling effects of green spaces 'in-situ' and within adjacent areas by up to 4.0K_{amb}. Within the scope of public space design, limited work has been carried out upon how such considerations function at a local/micro scale within the public realm (Tsiros, 2010).

Nevertheless, various authors have already analysed 'in-situ' tree characteristics to determine the impact of different vegetation species/layouts upon pedestrian thermal comfort levels (e.g., Almeida, 2006; Beckett, Freer-Smith, & Taylor, 2000; Erell et al., 2011; Fahmy and Sharples, 2011; Fahmy and Sharples, 2009; McPherson, 1984; Ochoa de la Torre, 1999; Picot, 2004; Taha et al., 1988; Shashua-Bar, et al., 2010; Shashua-Bar, Pearlmutter, & Erell, 2011). Moreover, and within the context of wholesome bioclimatic urban design projects, such know-how is already beginning to be applied (e.g., Coello and Philippe, 2015; Knuijt, 2013; TVK, 2013). In addition, more recent studies have also focused upon developing concrete urban design/planning priorities to attenuate urban microclimatic risk factors attributable to specific morphological composition (Norton et al., 2015), and concrete strategies to attenuate UHI effects (e.g., Akbari et al., 2016; Santamouris et al., 2016; Tan, Lau, & Ng, 2016; Wang, Berardi, & Akbari, 2016).

Of the measures suggested for Rossio, the alteration of paving material was not considered due to the presence of heritage decorated cobblestone paving within most the square. Nevertheless, such a design intervention still presents very promising microclimatic benefits in squares with low aspect ratios. In such urban spaces, and particularly within their central areas, there is an opportunity for public space design measures (such as paving materials) to address microclimatic exacerbations such diurnal G_{rad} intensity. When considering these effects upon other microclimatic variables, it becomes important to also counteract the effects of sensible heat loss from variables such as T_{surf} (and its potential influence upon T_{amb} values) when local albedo/emissivity values are low (Akbari et al., 2016; Georgakis and Santamouris, 2006; Santamouris, 2007; Stathopoulouet al., 2009; Santamouris et al., 2012; Santamouris, 2013). For this reason, further studies are required in Lisbon in order to reflect upon how such thermal sensitive measures can be explored in squares which are particularly vulnerable to diurnal G_{rad} intensities.

In the case the measures presented for Rossio, Table 2 illustrates the PET modifications that were calculated by the biometeorological model for each of the four locations. In the case of: (i) POI 2, once the location was cast in the sun after C3, $\Lambda T_{PET(2)}$ presented 'Moderate Heat Stress' as opposed to the previous 'Extreme Heat Stress'; (ii) POI 3, $\Lambda T_{PET(3)}$ fluctuated between 'Slight Heat Stress' and 'Moderate Heat Stress', which before ranged 'Extreme Heat Stress' after C3; (iii) POI 4, $\Lambda T_{PET(4)}$ fluctuated between 'Strong Heat Stress' and 'Moderate Heat Stress', which similarly to POI 3, previously ranged above 'Extreme Heat Stress' after C3; and lastly, (iv) POI 5, $\Lambda T_{PET(5)}$ presented a constant PS of 'Slight Heat Stress' after C3, which formerly obtained a PS of 'Moderate Heat Stress'.

The results of the study disclosed two fundamental aspects with regards to the interdisciplinary practice of local climate sensitive urban planning and design, namely the: (i) the identification of microclimatic risk factors within Mediterranean climates with hot and dry summers; and, (ii) exploration of conceptual public space design interventions that could potentially improve thermal comfort thresholds through pubic space design. Nevertheless, and given the projections of possible future climate change until the end of the century, such results were taken further in the subsequent section in order to consider how such meteorological aggravations can influence physiological comfort thresholds in the future.

2.2. The 'What if?' agenda

2.2.1. Future scenarios (SRES & RCP)

Future climatic projections provide a basis of quantifiable data, which in this case, relays to potential increases in temperature, amplified heatwaves, and augmented effects of UHI. Consequently, this raises the necessity to not only consider and generate adaptation measures, but to furthermore, correctly transpose such endeavours upon the built environment (Matos Silva and Costa, 2016; Nouri, 2015). In addition, such a transposition must always evaluate the bioclimatic performance of a site's configuration in order to obtain suitable, and integrated, outdoor urban design (Algeciras et al., 2016; Charalampopoulos et al., 2016; De Abreu-Harbich, Labaki, & Matzarakis, 2015; Krüger, Drach, Emmanuel, & Corbella, 2013; Lin et al., 2010; Matzarakis et al., 2016; Vanos, Warland, Gillespie, & Kenny, 2010). As a result, the practice of urban planning and design must thus undertake a flexible perspective which considers a wide range of future scenarios that are based upon scientific estimations of possible biometeorological and climatological outcomes until the end of the century.

Within this article, and in order to consider uncertainty whilst estimating potential climatic territorial impacts and anticipate potential resolutions, a range of socio-economic scenarios were used from the Special Report of Emission Scenarios (SRES) (IPCC, 2000). Among the four main SRES, the A1FI and A2A represent the cases with the fastest and most dramatic effects upon climate change predictions, while the B1A and B2A scenarios represent more attenuated levels of climatic variation. More recently, and within the fifth assessment report of the IPCC, these scenarios were replaced by the Representative Concentration Pathway (RCP) scenarios, namely: (i) RCP 8.5, based upon a future with no policy changes to reduce emissions − comparable to the SRES A1FI scenario; (ii) RCP 6, based upon the application of technologies and strategies for reducing GHG − comparable to the SRES B2 scenario; and, (iii) RCP 4.5, based upon ambitious reductions of global emissions − comparable to the SRES B1 scenario.

Focussing upon the worse-case scenario, and through the continued use of the disclosed thermo-physiological index, the 'What if?' agenda provided a means in which to launch the interrogation: *If the A1FI (or RCP 8.5) scenario came to fruition, what impacts could this have upon the local biometeorological environment in Rossio?*

2.2.2. Dataset modification and projected bioclimatic oscillations

In order to consider the impact of these scenarios upon projected PET values, Matzarakis and Amelung (2008) obtained all required variables from the Climatic Research Unit 1.0, and the HadCM3 datasets. As a result, and using the RayMan model, the PET and Mean Radiant Temperature (T_{mrt}) of each global grid were calculated based upon the following introduced parameters: T_{amb}, RH, *V* and cloud cover (manipulated from mean monthly sunshine fraction values). Also processed by the RayMan model, the historical period 1961–1990 served as bases for comparison in order to identify the respective deviation of PET until the end of the century. Dataset modification and projected bioclimatic oscillations

Based upon the previous, yet comparable version of the RCP 8.5 scenario (Rogelj, Meinshausen, & Knutti, 2012), the results of the A1FI SRES scenario illustrated drastic shifts towards warmer conditions around most of the world by 2100. With regards to the Mediterranean region, PET values revealed considerable increases in excess of 10 °C. Reflectively, these values were substantially higher than the estimated increase of up to 4.0 °C in air temperature by the end of the century (IPCC, 2014). Furthermore, and particularly within the Mediterranean area, the calculated PET could potentially surpass an increase of 15 °C. Such an increase, based upon the classification of Matzarakis and Rutz (2006) shown in Table 1, corresponds to three levels of increased physiological strain upon pedestrians. When considering the Iberian Peninsula, it was revealed that PET varied between +10 °C and +15 °C. More concretely, and in the case of Lisbon, an approximate variation of +10 °C and +12.5 °C was noted. In the case of the RCP 4.5 (or B1 SRES scenario), which corresponds to a considerably less grave scenario, projected modifications of bioclimatic conditions were more moderate. Within the Iberian Peninsula, and also for the JJA period, PET values ranged between +5.0 °C and +7.5 °C. Regardless, although a more attenuated oscillation from the previous scenario, still presents considerable aggravations of existing conditions. As a result, and established upon these variations for the Lisbon area, moderate PET increases of 10 °C and 6 °C were selected for the A1FI/RCP8.5 and B1/

Table 2
Existing mean PET values during day 3 and projected PET values after public space design interventions in each of the four POI.

	POI 2			POI 3		
	$\overline{PET_{D3}}$	Δ	$\overline{PET\Delta_{D3}}$	$\overline{PET_{D3}}$	Δ	$\overline{PET\Delta_{D3}}$
10:00-11:00	21.2	0.0K	21.2	31.8	-7.7K	24.1
11:00-12:00	23.8	0.0K	23.8	36.6	-9.9K	26.7
12:00-13:00	30.2	-5.3K	24.9	37.5	-11.6K	25.9
14:00-15:00	39.3	-9.8K	29.5	45.0	-14.2K	30.8
15:00-16:00	43.0	-9.9K	33.1	46.9	-16.6K	30.3
16:00-17:00	44.5	-9.4K	35.1	44.0	-16.2K	27.8

	POI 4			POI 5		
	$\overline{PET_{D3}}$	Δ	$\overline{PET\Delta_{D3}}$	$\overline{PET_{D3}}$	Δ	$\overline{PET\Delta_{D3}}$
10:00-11:00	32.9	-5.7K	27.2	30.5	0.0K	30.5
11:00-12:00	31.5	-5.9K	25.6	34.5	-0.9K	33.6
12:00-13:00	38.5	-6.3K	32.2	36.3	-1.9K	34.4
14:00-15:00	45.7	-10.5K	35.2	31.1	-4.7K	26.4
15:00-16:00	48.6	-12.3K	36.3	33.4	-3.9K	29.5
16:00-17:00	44.5	-10.9K	33.6	31.5	-3.6K	27.9

Key:	$\overline{PET_{D3}}$ PET values for Day 3	$\overline{PET\Delta_{D3}}$ Proj. PET values for Day 3 after suggested public space design interventions
	Colour coded based upon corresponding PS value represented in **Tbl.2**	

RCP4.5 scenarios, respectively.

2.3. Extension of physiological stress grades

Based on the investigative question launched within this study, and through the use of the 'What if?' agenda, a pilot analysis of the impacts upon the biometeorological conditions within Rossio could be approached. Constructed upon the modest oscillations of +10 °C and +6 °C upon the obtained PET values, the existing values presented in Table 1 required a significant adjustment. Based upon the increment of roughly 5 °C per physiological threshold within the existing grade system, three new grades were necessary beyond the initial 'Extreme Heat Stress' grade in order to articulately plot the projected PET results.

As shown in Table 3, the existing PS grades were expanded in order to include three additional categories beyond a PET value of 41 °C. Although further study is indispensible to determine the precise impact of such stress upon the human physiological system, this initial approach provides a basis of comparison with those obtained from existing measurements.

2.4. Dataset comparison

Based upon the disclosed increments of PET values upon the registered values during Day 3, within the four hottest POIs in the square, different sets of PET were thus cross-examined as presented in Table 4.

3. Results

As demonstrated in Fig. 3, when comparing the datasets, it was possible to verify: (i) a considerable oscillation of diurnal PET values between existing and future scenarios; and, (ii) the potential impact of the public space design interventions in each respective scenario.

In addition, when comparing the deviations between the B1A and the A1FI scenarios, it was noted that even in less severe climate change scenarios, the resulting projected bioclimatic environment still presented elevated 'Extreme' levels of physiological stress. Following this line of reasoning, this enforces the necessity for thermal sensitive public space design, which as indicated in Fig. 2, led to significant reductions in all assessed scenarios. Nevertheless, with the intention of identifying the most dramatic thermo-physiological implications upon the bioclimatic conditions in Rossio, the focus was turned to the A1FI scenario. As shown in Fig. 4 and as revealed by POI 3 and 4, the largest oscillations between the datasets were in locations that had elevated exposure to solar radiation. At these locations, and as shown by the $\overline{PET\Delta_{A1FI}}$ dataset, the microclimatic amelioration effects of the suggested public space design measures by the end of the century were significant. Between 15:00-16:00, and within POI 3, this was particularly evident when the $\overline{PET_{D3}}$ dataset surpassed that of $\overline{PET\Delta_{A1FI}}$ by almost $7.0K_{PET}$.

As a result, and comparatively to existing thresholds, this inferred that the amount of PS upon pedestrians could be significantly lower by the end of the century with the presence of the suggested solutions. Although to a lesser extent, this occurrence was also witnessed in POI 4. In the case of POI 2, although the $\overline{PET\Delta_{A1FI}}$ dataset did not drop below$\overline{PET_{D3}}$, both were almost identical after 14:00. Such outcomes indicate that the existing thermal stress felt currently in the square could potentially be the same by the end of the century with the presence of the proposed public space design interventions. Generally, and

Table 3
Grade Extension of Physiological Stress on human beings to accompany increased values beyond the Physiologically Equivalent Temperature (PET) value of 41 °C in light of projected estimates (see Table 1).
Source: (Adapted from, Matzarakis et al., 1999)

PET	Physiological Stress Grade	
18°C	Slight Cold Stress	Existing Grades
	No Thermal Stress	
23°C	Slight Heat Stress	
29°C	Moderate Heat Stress	
35°C	Strong Heat Stress	
41°C	Extreme Heat Stress (LV1)	
46°C	Extreme Heat Stress (LV2)	New Required Grades
51°C	Extreme Heat Stress (LV3)	
>56°C	Extreme Heat Stress (LV4)	

in most POIs, the $\overline{PET_{A1FI}}$ dataset presented radical increases in physiological stress, especially in POIs located within the center of the square.

However, and in the case of POI 5 (identified as the coolest of the four hottest POIs), the projected thermal stress levels were less accentuated. Although attributed to the lower amount of received diurnal solar radiation, this still did not devalue that the projected increases in PS would correspond to those presently found in the center of the square.

3.1. Grid network

3.1.1. Postulation of physiological stress distribution

Based on the obtained PET oscillations to inform a projective distribution of physiological stress, a hypothetical 5m by 5m grid network was considered throughout the entire square. In order to preserve precision whilst assessing PS values around the square, the established grid enabled a more concise: (i) consideration of shade upon pedestrianized areas as a result of the street trees; (ii) contemplation of hotter surface temperatures around the square; and, (iii) definition of shade patterns cast by encircling structures such as building façades and square amenities (including those resultant of the proposed solutions).

Although this approach indicates just a synoptic and initial estimation of thermal comfort distribution around the entire square, the results obtained at each POI were used to inform how similar locations could influence pedestrian PS thresholds. More specifically, in liaison with previous simulations undertaken by the authors in the initial study, and considering the results from the RayMan model during the hottest diurnal hour, i.e. C5, between 15:00 and 16:00:

- POI 1 provided a reference for an area of the western sidewalk that was not shaded by vegetation, yet, that was cast in shade cast by the western façade of the square during the afternoon
- POI 2 provided a reference for an area of the eastern sidewalk that was not cast in the shade by a building façade, yet, was cast in the shade by an encircling vegetative crown in the afternoon

Table 4
Description of the Physiologically Equivalent Temperature (PET) datasets at each Point of Interest (POI) before and after interventions for existing and future A1FI/RCP8.5 and B1/RCP4.5 scenarios.

Existing Scenarios	
$\overline{PET_{D3}}$	Representing existing PET without public space design interventions
$\overline{PET\Delta_{D3}}$	Representing existing PET with public space design interventions
Projected Scenarios	
$\overline{PET_{B1A}}$	Representing projected PET without public space design interventions in a scenario with ambitious reductions of global emissions
$\overline{PET\Delta_{B1A}}$	Representing projected PET with public space design interventions in a scenario with ambitious reductions of global emissions
$\overline{PET_{A1FI}}$	Representing projected PET without public space design interventions in a scenario with no policy changes to reduce global emissions
$\overline{PET\Delta_{A1FI}}$	Representing projected PET with public space design interventions in a scenario with no policy changes to reduce global emissions
Specific diurnal period	
$\overline{PETX_{(C5)}}$	PET dataset *X* at C5 (i.e. between 15:00-16:00)

POI 2	$\overline{PET_{D3}}$	$\overline{PET_{B1A}}$	$\overline{PET_{A1FI}}$	$\overline{PET\Delta_{D3}}$	$\overline{PET\Delta_{B1A}}$	$\overline{PET\Delta_{A1FI}}$
10:00-11:00	21.2	27.2	31.2	21.2	27.2	31.2
11:00-12:00	23.8	29.8	33.8	23.8	29.8	33.8
12:00-13:00	30.2	36.2	40.2	24.9	30.9	34.9
14:00-15:00	39.3	45.3	49.3	29.5	35.5	39.5
15:00-16:00	43.0	49.0	53.0	33.1	39.1	43.1
16:00-17:00	44.5	50.5	54.5	35.1	41.1	45.1
POI 3						
10:00-11:00	31.8	37.8	41.8	24.1	30.1	34.1
11:00-12:00	36.6	42.6	46.6	26.7	32.7	36.7
12:00-13:00	37.5	43.5	47.5	25.9	31.9	35.9
14:00-15:00	45.0	51.0	55.0	30.8	36.8	40.8
15:00-16:00	46.9	52.9	56.9	30.3	36.3	40.3
16:00-17:00	44.0	50.0	54.0	27.8	33.8	37.8
POI 4						
10:00-11:00	32.9	38.9	42.9	27.2	33.2	37.2
11:00-12:00	31.5	37.5	41.5	25.6	31.6	35.6
12:00-13:00	38.5	44.5	48.5	32.2	38.2	42.2
14:00-15:00	45.7	51.7	55.7	35.2	41.2	45.2
15:00-16:00	48.6	54.6	58.6	36.3	42.3	46.3
16:00-17:00	44.5	50.5	54.5	33.6	39.6	43.6
POI 5						
10:00-11:00	30.5	36.5	40.5	30.5	36.5	40.5
11:00-12:00	34.5	40.5	44.5	33.6	39.5	43.6
12:00-13:00	36.3	42.5	46.3	34.4	40.4	44.4
14:00-15:00	31.1	37.1	41.1	26.4	32.4	36.4
15:00-16:00	33.4	39.4	43.4	29.5	35.5	39.5
16:00-17:00	31.5	37.5	41.5	27.9	33.9	37.9
	Without Interventions			With Interventions		

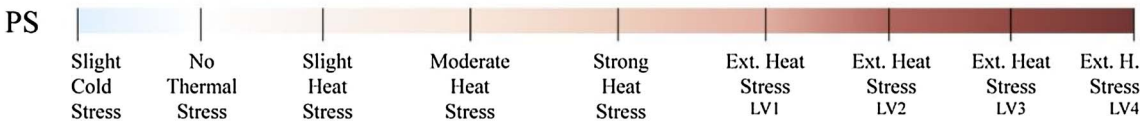


Fig. 3. Comparison of existing PET averages during Day 3 with future A1FI/RCP8.5 and B1/RCP4.5 scenarios until the end the century.

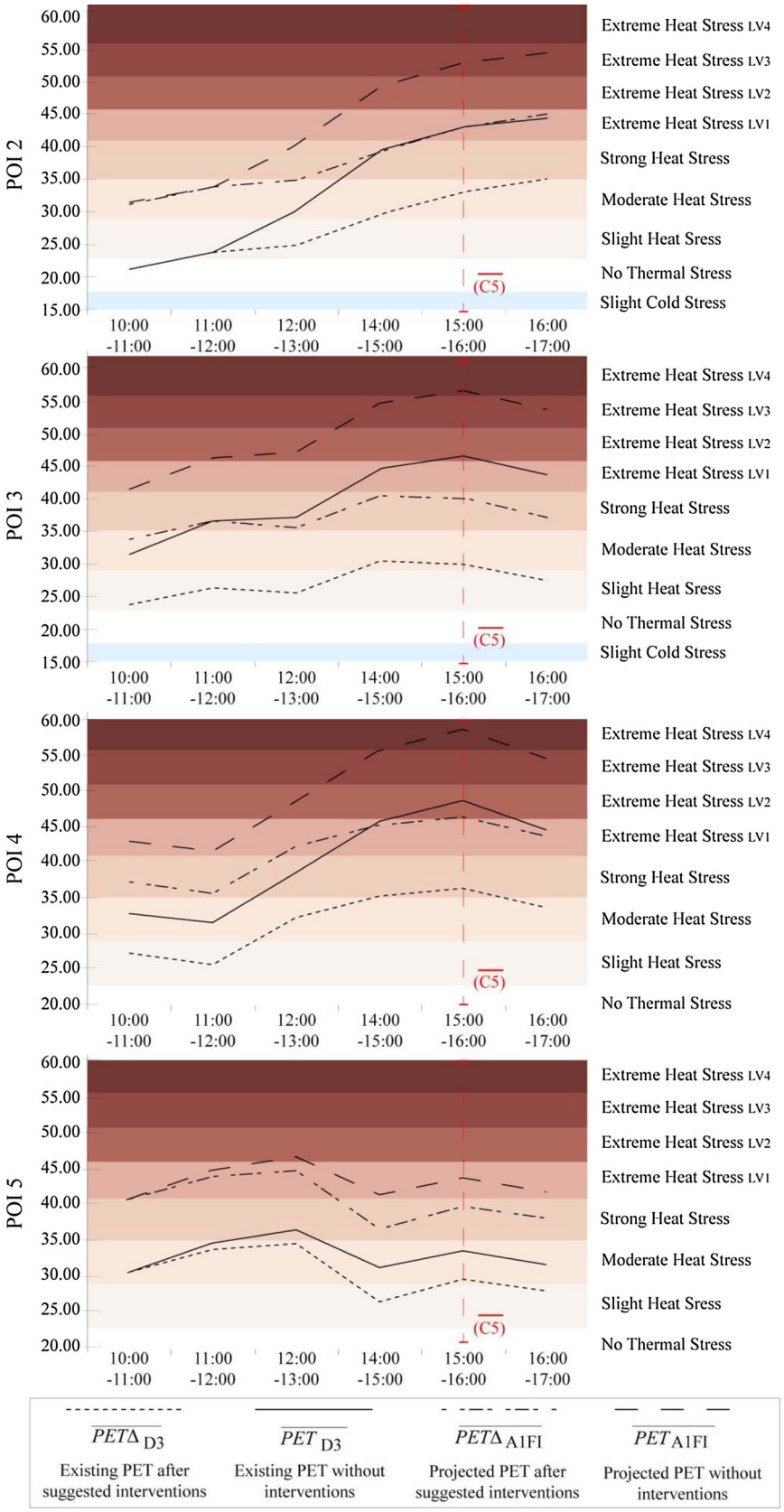


Fig. 4. Comparison of existing PET averages during Day 3 (before and after interventions) with future projections until the end the century, C5 emphasised by red line which identifies period where majority of POI's witnessed highest stress levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

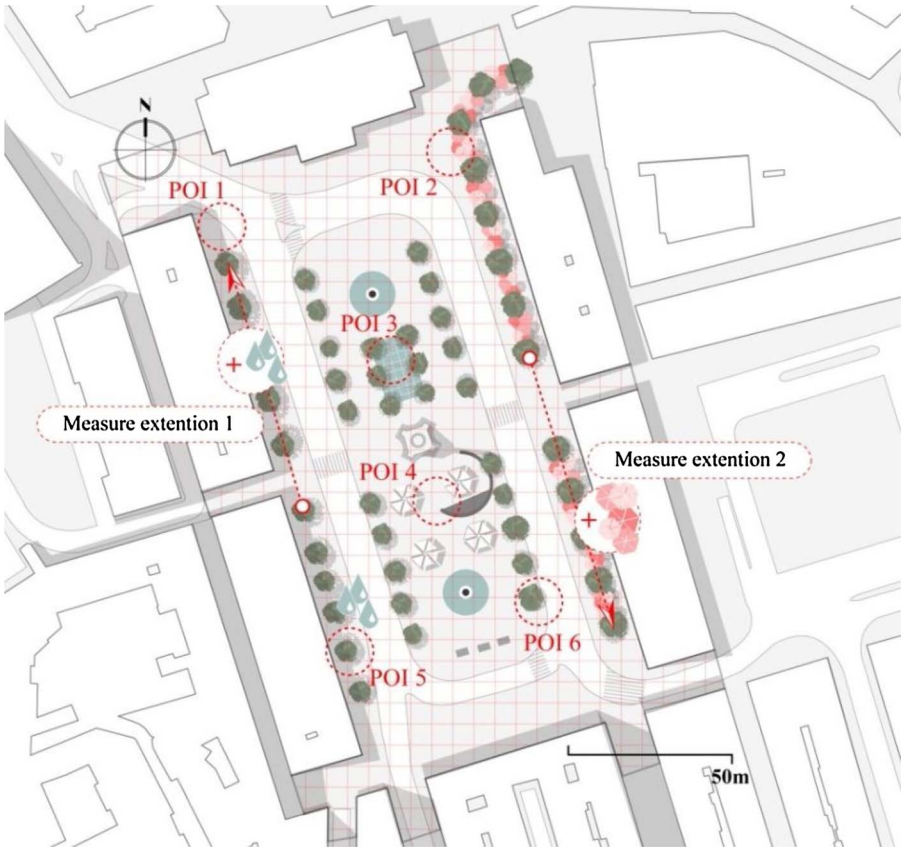


Fig. 5. Gridded layout of Rossio with proposed public space design interventions with extensions on western and eastern sidewalks.

- POI 3 provided a reference for the northern central area of the square that contained no source of shade
- POI 4 provided a reference for the southern central area of the square that also contained no trace of diurnal shade
- POI 5 provided a reference for an area of the western sidewalk that was both shaded by vegetation and cast by the western façade of the square
- POI 6 provided a reference for areas within the central square that were shaded by a vegetative crown

3.2. Measure extension

As the distribution of PS was considered around the entire square, it was also decided to expand two of the suggested public space design interventions in order to consider how thermal comfort could be modified throughout the entire western and eastern sidewalks. More concretely, and as shown Fig. 5, in the case of: (i) POI 1–considering the western sidewalk, the five trees between POI 1 and 5 were also considered to have the misting system within the branches of the tree crown; and, (ii) POI 5–considering the eastern sidewalk, the use of nylon canopies between the vegetation was extended to the remaining five trees to the south.

Also referring to the values obtained at each POI, and in order to consider how PS thresholds could be modified throughout the entire western and eastern sidewalks; the solutions proposed for POI 5 (water misting system), and POI 2 (nylon canopies), were extended as shown in Fig. 5 (■ See Appendix C). In the case of the western sidewalk (i.e. measure extension 1), the five trees between POI 1 and 5 were also considered to have the misting system within the branches of the tree crown. On the south-eastern sidewalk (i.e. measure extension 2), the use of nylon canopies between the vegetation was extended to the remaining five trees to the south.

As shown in Fig. 5, the overlapped grid network provided a base to determine the dimensional extents of both existing and new public space design implementations. Such dimensions are what provided a foundation to differentiate the PS attributed to each respective grid.

Although rudimentary, it provided a means to carry out a synoptic thermal evaluation of the entire square based on existing PET values in locations with similar characteristics. As a result, and considering the outcomes shown in Fig. 4, when analysing the physiological results with the use of the grid network, and as presented in Table 4, four different scenarios were subsequently applied.

4. Discussion

4.1. Intensity of physiological stress

4.1.1. Existing scenario

As expected, $\overline{PET\Delta_{D3(C5)}}$ revealed the lowest PS thresholds of all four datasets. In particular, there was a significant reduction of PS within the center of the square. Such descents resulted from the public space design interventions within POI 3/4 which lowered physiological strain by up to three levels.

Given the fact that the western side of the square was cast in the shade, the influences of the suggested public space design interventions were smaller in comparison to the results obtained within the eastern sidewalk. As revealed by $\overline{PET\Delta_{D3(C5)}}$ the nylon canopies reduced PS by up to two levels resultant of the shade cast upon the sidewalk, thus matching the PS expected on the western sidewalk (Fig. 6**a**). The continuous shade upon the sidewalk enabled solar radiation to be reduced over a larger area, in comparison to the lesser and intermittent reduction demonstrated by$\overline{PET_{D3(C5)}}$.

As indicated in Fig. 6**b**, the$\overline{PET_{D3(C5)}}$ revealed that areas in the center of the square can already obtain a PS of 'Extreme Heat Stress Lv.2'. Thus, all grids that did not receive shade within the center of the square were attributed this PS level. In addition, and considering that the road surface obtained very high temperatures, road areas located around the center of the square were also attributed the same PS level. In the case

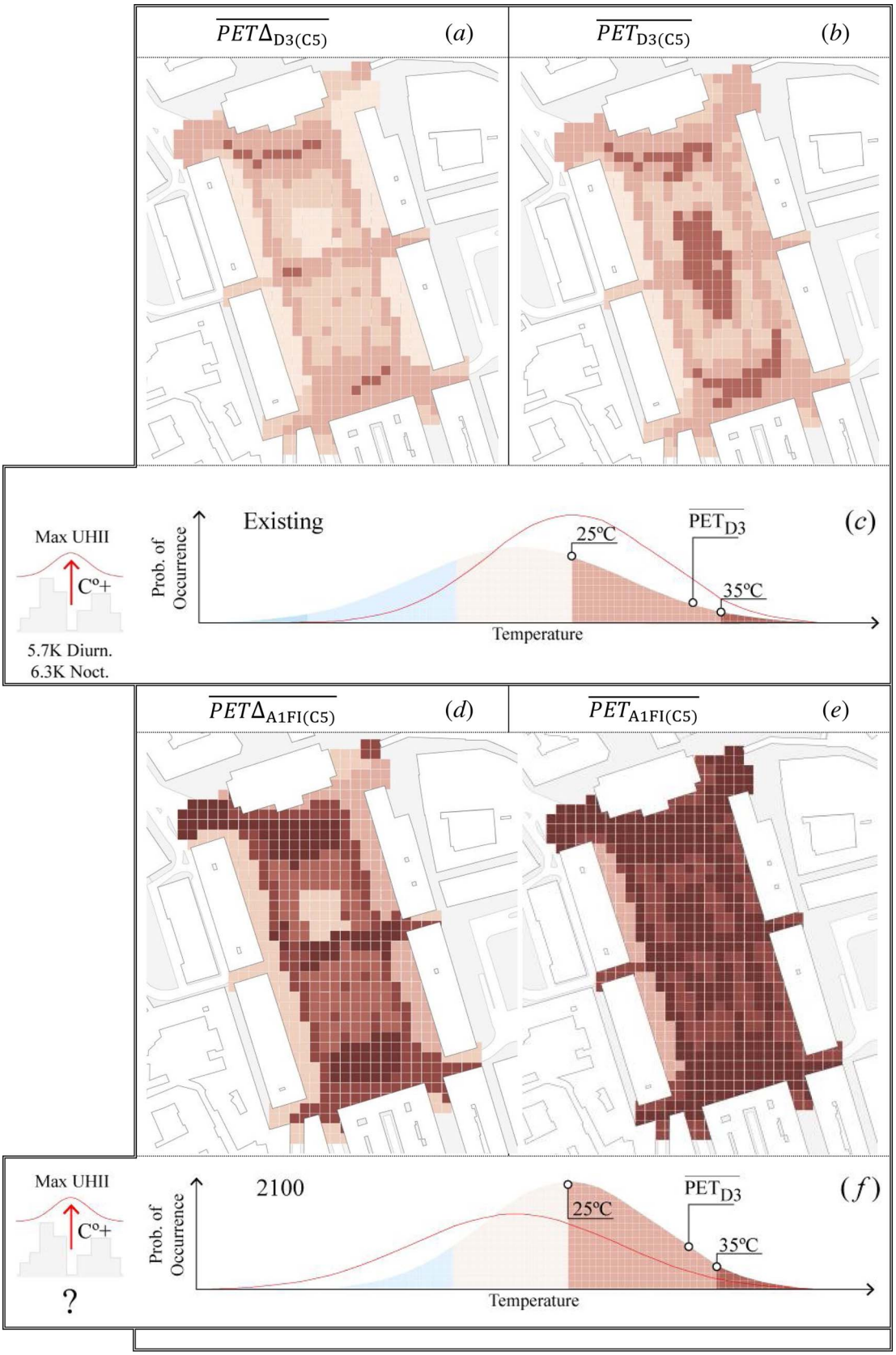


Fig. 6. Distribution of Physiological Stress around Rossio for existing and projected climate.

of$\overline{PET\Delta_{D3(C5)}}$, due to the lower PS thresholds obtained within the northern and southern extremities of the square's center, fewer grids were attributed such a PS grade.

4.1.2. Future scenario

When considering the datasets $\overline{PET\Delta_{A1FI(C5)}}$ and $\overline{PET_{A1FI(C5)}}$, the results demonstrated a dramatic increase of overall PS around the entire

square. Founded upon the outcomes presented in Fig. 6, the modest increase of +10 °C in PET dramatically shifted PS thresholds, especially in the case of $\overline{PET}_{A1FI(C5)}$ where no solutions were introduced within the square. Even with the presence of vegetation/shade, wind currents, and building shade, most of the square presented either a PS of 'Extreme Heat Stress Lv.3′ or 'Extreme Heat Stress Lv.4′ resultant of PET values exceeding that of 51 °C or 56 °C, respectively. Even though not located in the center of the square, the eastern sidewalk also presented similar increases of physiological strain by up to three levels.

The coolest region in the square was the western sidewalk, which although cast in the shade, still obtained a PS of 'Extreme Heat Stress'. This grade was obtained by the addition of 10 °C in PET upon the existing PS of 'Moderate Heat Stress'. Such results thus imply that if no action is taken until the end of the century, the coolest sensation a pedestrian could feel in Rossio could be equivalent to what is currently felt in the center of the square today.

Comparatively, the $\overline{PET\Delta}_{A1FI(C5)}$ presented more attenuated PS thresholds as a result of the proposed solutions. Within the western sidewalk the combination of the shade cast by the building façade and the misting mechanism led to a PS threshold of 'Strong Heat Stress'. In the case of the eastern sidewalk, the combination of the added nylon canopies with the increased northern *Tipuana Tipu* tree-line also decreased PS by three levels comparatively to the $\overline{PET}_{A1FI(C5)}$ dataset. Within the center of the square, the proposed shelter canopies for POI 4 led to a reduction of two PS levels due to the attenuation of solar radiation. Nevertheless, it was still noted a substantial PS of 'Extreme Heat Stress Lv.2′, which corresponds to the physiological strain felt today with no attenuation measures. Still within the center of the square, the most drastic reduction however was identified in POI 3, which presented a vast reduction of four PS levels from 'Extreme Heat Stress Lv.4′ to 'Strong Heat Stress'.

4.2. Periodicity of physiological stress

Similarly to the intensity of physiological stress, the periodicity and duration of such thermal stimuli also required scrutiny. In order to undertake this analysis, both Control and Projected annual figures were required for the Lisbon area. This information was retrieved from the research project Climate Change in Portugal, Scenarios, Impacts and Adaptation Measures conducted by Santos and Miranda (2006) who utilised regional climate models to determine existing and potential future aggravations of extreme temperatures and heatwaves at a regional scale.

As indicated by Miranda (2006), when considering the occurrence of climatological occurrences such as 'Very Hot Days' (T_{amb} > 35 °C), 'Summer Days' (T_{amb} > 25 °C), and Heatwaves (Consecutive days where max T_{amb} > 32 °C), specifically for the Lisbon region, there will be a considerable increase between existing figures and those projected for the end of the century. Accordingly, and as indicated by existing literature, it is 'very likely' that heatwaves will occur more often and last longer by the end of the century (IPCC, 2014), including within the European and Mediterranean region (Kuglitsch, Toreti, Xoplaki, Della-Marta, & Zerefos, 2010). Furthermore, the IPCC also stipulated in their fifth assessment report that the influence of prospective climate change upon heatwaves shall be more significant than the impact upon global average temperatures (IPCC, 2013).

In the case of Western Europe in particular, and considering the heatwave of 2003, it was enforced that European countries, such as Portugal, required additional measures to warn, cope, and prevent the recurrence of such events (Kovats and Ebi, 2006; Matzarakis, 2016). More concretely, and within the district of Lisbon, between the 29th of July and the 13th of August 2003, it was identified by Nogueira et al. (2005) that: (i) 15 days had maximum temperatures above 32 °C; (ii) there was a noteworthy consecutive run of 10 days with temperatures superior to 32 °C; and finally, (iii) there was a 5 day period which consecutively experienced temperatures above 35 °C. When considering such impacts upon public health, an estimated mortality rate increase of 37.7% (i.e. corresponding to 1316 excess deaths) in comparison to what would be expected under normal conditions.

4.2.1. Existing scenario

Based upon Miranda (2006), the existing physiological results from the $\overline{PET}_{D3}$ dataset could be evaluated in terms of annual periodicity. Firstly, and obtained from the hottest day, the absolute maximum T_{amb} measured on site was of 32.9 °C, a value that was obtained at POI 2, during Cycle 6, measurement 5 (■ See Appendix A). This infers that although the dataset revealed 'Extreme Heat Stress' levels, and met the 'Summer Day' criteria, the maximum recorded T_{amb} was insufficient to fall under the 'Very Hot Day' classification as synoptically represented in Fig. 6**c**. The implication of this divergence suggests that under present conditions, there already is a possibility of 10–20 days rendering hotter ambient temperatures, albeit by a small margin.

4.2.2. Future scenario

Based upon SRES A2 projections for the end of the century, it was identified that within the A2 scenario, areas such as Lisbon could potentially witness a: (i) total of 50 days a year with diurnal temperatures surpassing that of 35 °C, i.e., labelled as a 'Very Hot Day'; (ii) doubling in duration of days that consecutively surpass temperatures of 35 °C, (implying a potential span of 20 uninterrupted days with such diurnal temperatures); (iii) radical upsurge of 'Tropical Nights' with elevated temperatures, raising from 20 to a potential 80 annual nights where the minimum T_{amb} surpasses that of 20 °C; and lastly, (iv) considerable increase of 'Summer Days' (potentially varying up to 180 days). This was represented in Fig. 6**f**, whereby half the year is attributed a classification of 'Summer Day' which implies reaching a diurnal T_{amb} of 25 °C.

More seriously however, A2 projections suggest that by the end of

Table 5
Physiologically Equivalent Temperature Load (PETL) for each assessed scenario.

	Set of Days		Single Day (Based upon Day 3)			
	Existing Scenario		Existing Scenario		Projected Scenario	
	$\overline{PETL}_{AD(C5)}$	$\overline{PETL}_{NC(C5)}$	$\overline{PETL\Delta}_{D3(C5)}$	$\overline{PETL}_{D3(C5)}$	$\overline{PETL\Delta}_{A1FI(C5)}$	$\overline{PETL}_{A1FI(C5)}$
POI 1	8.7	9.2	≈ 9 *1	≈ 9 *1	≈ 15 *2	≈ 20.5 *3
POI 2	13.2	16.4	10.1	20.0	20.1	30.0
POI 3	16.4	20.0	7.3	23.9	17.3	33.9
POI 4	15.2	19.2	13.3	25.6	23.3	35.6
POI 5	9.5	8.2	6.5	10.4	16.5	20.6
POI 6	10.9	12.9	≈ 15 *2	≈ 15 *2	≈ 25.5 *4	≈ 30.5 *5

*Based on subtraction of *A* (i.e., 23.0) from Mid-Range (MR) value of: 1 = Moderate Heat Stress; 2 = Strong Heat Stress; 3 = Extreme Heat Stress Lvl.1; 4 = Extreme Heat Stress Lvl.2; 5 = Extreme Heat Stress Lvl.3

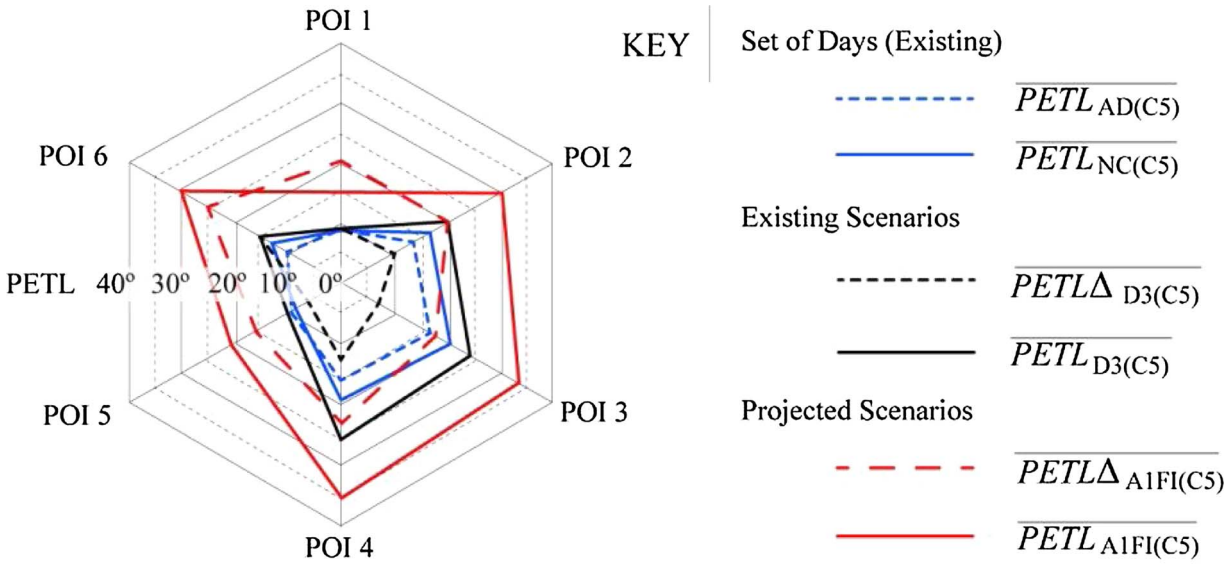


Fig. 7. Radar Chart of Distribution of Physiologically Equivalent Temperature Load (PETL) at C5 within the different assessed scenarios.

the century, there can potentially be up to 50 annual days with hotter diurnal temperatures. In addition, almost half of these days can potentially consecutively follow one another. Also represented in Fig. 6**f**, and based on the definition of Calheiros (2006), the occurrence of consecutive days with similar temperatures as those found in $\overline{PET_{D3}}$ (constituting a heatwave), can also dramatically increase by the end of the century.

For these reasons, and specifically considering Lisbon's existing and projected climatological trends, the duration of a thermal stimulus becomes just as important as its respective intensity. Accordingly, although the PET from Day 3 (hottest of all site visits) may currently represent a comparatively infrequent occurrence, future projections indicate that such conditions: (i) will very likely be the new standard, and resulting PS levels will become customary instead of intermittent; and, secondly (ii) can recurrently be exceeded by hotter days that further augment PS levels, i.e. where diurnal T_{amb} surpasses a value of 35 °C. In addition, and having in mind that the A2 projections are based upon a more attenuated SRES projection in comparison to the A1FI scenario, such deliberations should further refer to the heatwave in Lisbon during 2003, which had a dramatic impact upon urban public health and mortality rates.

4.3. Overall physiological stress & physiologically equivalent temperature load

In order to consider an overall comparison between the different presented thermal environments in Rossio, PET Load (PETL) was utilised to compare how the obtained PET results differ from the proposed optimal PET value. This parameter was developed by Charalampopoulos et al. (2016) in order to identify the discrepancy of the mean hourly PET value in comparison to the optimal established PET values in various locations.

$$PETL = PET_h - A$$

Whereby: $PET_h \rightarrow$ is the average hourly PET value; $A \rightarrow$ is representative of the PS grade of 'Comfortable'

Applying this parameter to the case study of Rossio, and since the analysis conducted in Fig. 6 is established upon C5 (i.e., between 15:00-16:00), PET_h was based upon the PET values obtained during this hour. Since the *A* factor can be calibrated depending on the specified PET ranges (Hwang, Lin, & Matzarakis, 2010; Charalampopoulos et al., 2016; Lin and Matzarakis, 2008; Lin, 2009), a PET value of 23.0 °C was selected as it represented the upper limit of the 'Comfortable' classification as illustrated in Tables 1–3.

The overall results for every examined dataset during C5 were presented in Table 5. On the left side of the table, both $\overline{PETL}_{AD(C5)}$ and $\overline{PETL}_{NC(C5)}$ are indicative of the PET obtained during C5 during all days, and days in which there were no clouds (i.e., days 1/2/3/5/7). On the right side of the table the results obtained from the four datasets obtained for day 3 were divided into existing and projected scenarios.

Fig. 7 presents the distribution of thermal load beyond what is considered 'comfortable' in PS terms within the different datasets and scenarios. Such results indicate: (i) the small yet clear deviation of PS between $\overline{PETL}_{AD(C5)}$ and $\overline{PETL}_{NC(C5)}$ datasets, due to extraction of days with no clouds from the general dataset, especially in POIs with limited shading (i.e. POI 2/3/4); (ii) the large disparity of PS between existing scenarios (i.e. $\overline{PETL\Delta}_{D3(C5)}$ and $\overline{PETL}_{D3(C5)}$) as a result of proposed public space design interventions within POI 2/4/5, and a particularly in POI 3; (iii) the comparatively dramatic increase of thermal load in the cases of $\overline{PETL\Delta}_{A1FI(C5)}$ and $\overline{PETL}_{A1FI(C5)}$, particularly within the middle of the square, such as in the case of POI 4 in the latter scenario which obtained a drastic PETL value of 35.6 °C above the established 'comfortable' stress grade; and lastly, (iv) the overlapping of datasets within the different scenarios, such as $\overline{PETL\Delta}_{A1FI(C5)}$ that integrates the public space design interventions by the end of the century, with those currently found on site today without any interventions as indicated by $\overline{PETL}_{D3(C5)}$ in POIs 2/3/4.

4.4. Urban heat island effects

Finally, the last considered factor within the study was the implications of UHI upon the PS levels found in Rossio. Although the section raised more questions than answers (particularly for future scenarios), when considering studies such as the one conducted by Alcoforado et al. (2014) that focused upon the case of Lisbon, it was suggested that: (i) thermal stress thresholds are considerably intensified due to the effects of UHI; (ii) steps ought to be taken to adapt to future climatic conditions which are already being felt within the city; and lastly, (iii) the UHI effect is stronger during the summer, obtaining a maximum hourly average of up to 6.3 °C. By comparatively counting the number of times a predetermined site was the hottest or coldest, it was identified that the site 'Restauradores' was the warmest location 64.9% of the time during the day, and 79.6% during the night. Opportunely, of the five measurement sites, this location was located just north of Rossio (located south of 'Avenida de Liberdade', indicated by point 'd' in Fig. 1**a**.

Such results verify the outcomes obtained by (Andrade, 2003; Alcoforado et al., 2005) who identified that stronger UHI intensities during the summer are normally found within the southern regions of the city. As indicated by studies conducted by Lopes (2002), it was suggested that the urban morphology, or urban 'roughness', can have a strong sheltering effect upon wind patterns, which can consequently influence UHI patterns. Within the same study, it was also identified that there is a potential of considerable future wind speed reductions within the city center as a result of augmented urban 'roughness' quantities further impeding northern winds to permeate southern regions of the city. However, this cause-and-effect relationship between these three characteristics has proven to be more complex than initially thought. As illustrated by Lopes et al. (2013), although it was verified that increases in wind speed led to a decrease of UHI intensities, the absence of wind (or prevailing atmospheric calm) did not lead to respective augmentations of the UHI.

As suggested by Oke (1976), the increase of UHI intensities is restricted to new urban structures requiring the demolishing of others once a certain amount of urban density is reached. This being said, when considering the urban energy balance as suggested by Oke (1988):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

Whereby: $Q^* \rightarrow$ net of all-wave radiation; $Q_F \rightarrow$ anthropogenic heat flux; Q_H is the flux of sensible heat; $Q_E \rightarrow$ the flux of latent heat; $\Delta Q_S \rightarrow$ heat stored within the urban fabric; $\Delta Q_A \rightarrow$ net heat advection

It is vital to consider that the energy balance is transient given the dependency upon the constant fluctuation of urban radiation. For instance, when approaching the net of all wave radiation, changes in non-temperature factors such as short and long wave radiation produce direct repercussions upon outdoor comfort thresholds (Algeciras et al., 2016; Charalampopoulos et al., 2016; Matzarakis and Amelung, 2008). This being said, when considering the resulting modifications upon PS in Rossio, such repercussions were evident when considering the simple yet clearly divergent $\overline{PETL}_{NC(C5)}$ results obtained between $\overline{PETL}_{AD(C5)}$.

When considering future horizons, and due to the delicate equilibrium of the urban energy balance, it is here suggested that although downtown Lisbon may not increase in urban/structural density (or 'roughness'), current UHI intensity levels should not be considered stagnant during the twenty-first century. Instead, identified T_{amb} values such as 6.3 °C (Alcoforado et al., 2014), should be approached as a 'base value' which can be offset by modifications to the urban energy balance.

Beyond the results of this study, and exemplified by other prominent international studies, there already is evidence that local measures such as pavement/surface materials, vegetation, water features can considerably influence UHI intensities. As suggested by Santamouris et al. (2016) between the investigated 220 large scale projects that incorporated some form of local measure to reduce local thermal stress and UHI levels, the average peak T_{amb} drop was close to 2 °C. Similarly, within the city of Toronto, and through the combination of cool pavements/roofs, and vegetative shading, a T_{amb} reduction of up to almost 1 °C was identified (Wang et al., 2016). Moreover, and within Toronto's university campus, through the application of green roofs alone, potential reductions of average peak T_{amb} up to 0.4 °C were identified at pedestrian level (Berardi, 2016). Focusing upon vegetation at pedestrian level through the implementation of urban tree design approaches to combat UHI effects in Hong Kong, Tan et al. (2016) identified a potential T_{amb} reduction of 1.5 °C. Such results raise the opportunity for complementary future studies within Lisbon's public spaces, particularly in those presenting lower aspect ratios; not only due to their higher exposure to radiation levels, but more importantly, due to the opportunities to address such vulnerabilities through creative public space design.

For this reason, and considering Oke's energy balance specifically for the urban environment, the implementation of thermal sensitive public space design measures should premeditate upon the counteraction of: (i) the stress associated to the projected increase in the frequency, intensity and consecutiveness of annual summer/hot days by modifying the net/balance of all wave radiation, such as reducing the amount of incoming short-wave radiation upon pedestrians during such periods; (ii) the escalation of urban anthropogenic emissions associated to urban cooling energy requirements (such as air conditioning (Santamouris, 2016)) which as identified by Isaac and Vuuren (2009) can increase by up to 166% by 2100; (iii) the heat storage within the urban fabric of surface materials (such as pavements (Stathopoulou et al., 2009)); and, (iv) urban heat accumulation by insuring the permeability of wind currents in hotter regions of the city, which can have considerable influences upon thermal comfort levels, even in lower aspect ratios (Algeciras and Matzarakis, 2017).

For these reasons, and as expressed by '?' in Fig. 6**f** for future projections, the uncertainty of future UHI values/intensities thus becomes interlinked with action of Man, and his respective impacts upon the urban energy balance as suggest by Oke (1988). As described within this study, and as collaborated by other bioclimatic studies, attenuation of UHI intensities is possible, yet invariably, is only possible if local bottom-up action is undertaken within built environment. In the case of Lisbon, this is intrinsically concomitant with the decision to act in public spaces such as Rossio which are located in areas that are particularly vulnerable to UHI effects.

5. Conclusions

The use of the thermophysiological index PET enabled this study to compare various thermal scenarios that consider implications upon Rossio's existing and future biometeorological environments. Although based upon evaluations of future variations of radiation fluxes, (i.e., countenancing such assumptions of an increase of 10 °C in PET) such explorations allow for future climatic trends to be assessed. Even though the methods used in this bioclimatic study are still maturing, and thus require further study, it nevertheless marks a potential departure from more top-down orientated projections which do not include important meteorological factors (such as radiation fluxes). More specifically, simplistic reflections and/or projections of T_{amb} are continually proving to be insufficient for interdisciplinary practices such as public space design. As a result, the exploration and application of associated biometeorological studies are incessantly proving to be indispensable when addressing the existing, and future, bioclimatic environment of the urban public realm.

Within this study, and by considering existing and future PS thresholds through the application of the 'What if?' agenda, it was possible to explore what could happen within a public space that is already suffering from climatic aggravations. In order to do so, the existing PS grades were expanded beyond the initial > 41 °C threshold to plot the projected results for the end of the century given the A1FI/RCP8.5 scenario. Such a modification was seen to be synonymous with the necessity to question whether current approaches to thermal comfort require further contemplation based upon possible unprecedented aggravations of the urban climate within the public realm.

This being said, and as revealed by the distributive PS analysis around the square, existing diurnal and hourly PET datasets already revealed 'Extreme Heat Stress Lv1/2′ within the center of the square. In addition, such PS thresholds were identified during a day which, although by a small margin, did not reach the delineated 'Very Hot Day' classification. More specifically, as the hottest registered T_{amb} value measured on site was a near 32.9 °C, this implied that such PS results can feasibly be more drastic during a day in which maximum T_{amb} values surpass the 35 °C threshold.

When approaching the augmentation of PET in the A1FI/RCP8.5 scenario, the comparative increase of PS levels was drastic. Such disparity was revealed by the dataset which presented the bioclimatic

environment of Rossio with no proposed public space design interventions. Furthermore, regardless of the presence of vegetation/shade, wind currents, and building shade, most of the square presented a PS threshold ranging between 'Extreme Heat Stress Lv.3 and 4', with PET values exceeding that of 51 °C and 56 °C. In parallel, and when considering both the datasets which incorporated public space design interventions, it was identified that the proposed solutions were able to substantially reduce PS levels, particularly in locations prone to high levels of solar radiation. During C5, such results were also confirmed by the PETL, when oscillations from the base 'Comfortable' physiological threshold reduced by −9.9 °C in POI 2, −16.6 °C in POI 3, and −12.3 °C for POI 4 with the presence of the public space design interventions.

Nevertheless, and although the public space design proposals presented promising reductions of existing physiological strain, when considering future horizons, such diminutions proved narrow. As illustrated by the study: (i) even with suggested public space design interventions, the lowest obtained PS grade was of 'Strong Heat Stress'; more seriously however, (ii) in the case where no action is taken until the end of the century within a A1FI/8.5 scenario, the lowest obtained PS grade was of 'Extreme Heat Stress', a threshold which corresponds to what would be felt today within the hottest regions of the square. For this reason, and when considering future augmentations of PET, this study argues that further action is required, whereby its urgency will systematically accompany the progression of potential climatic aggravations projected for the end of the century. To this end, there is an opportunity for a further study which focuses upon prior timeframes (such as 2040 and 2070) in order to identify the progression of these climatic aggravations before reaching the temporal slice discussed in this study.

This being said, and even at a more distant horizon, this study enforces that action is required both at an awareness level, and at a design level which is facilitated by an exploration which concedes the possibility that our cities may in fact have to deal with extreme scenarios by the end of the century. In this sense, such preparations require early and cautious design and planning efforts, that are firstly enabled by flexible examinations such as the 'What if?' agenda; and secondly, backed by projections which consider sufficient meteorological factors which can be used to evaluate the potential future bioclimate of our urban public realm.

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Appendix A. EQUIPMENT & MEASUREMENTS Adapted from (Nouri & Costa, 2017b).

	A.1	Equipment used during the field study			
	Equipment Name / Model #	Measurement	Value Output	Accuracy	Resolution
1	KESTREL 4600BT©	V	m/s	± 3% (of disp. reading)	0.1 m/s
		T_{amb}	Cº	± 0.5	0.1 Cº
		RH	%	± 3.0	0.1%
2	KKMOON SM206©	G_{Rad}	W/m^2	± 10	0.1 W/m^2
3	BENETECH GM550©	T_{surf}	Cº	1.5%	0.1 Cº

A.2 Meteorological measurement structure for the eight minutes at each Point of Interest (POI) during each of the six hourly analysis Cycles (C1-6) throughout each daily visit to the site in order to obtain eight recordings of each meteorological measurement

	10:00-11:00 (C1)	11:00-12:00 (C2)	12:00-13:00 (C3)	14:00-15:00 (C4)	15:00-16:00 (C5)	16:00-17:00 (C6)
POI 1	10:00/08	11:00/08	12:00/08	14:00/08	15:00/08	16:00/08
POI 2	10:10/18	11:10/18	12:10/18	14:10/18	15:10/18	16:10/18
POI 3	10:20/28	11:20/28	12:20/28	14:20/28	15:20/28	16:20/28
POI 4	10:30/38	11:30/38	12:30/38	14:30/38	15:30/38	16:30/38
POI 5	10:40/48	11:40/48	12:40/48	14:40/48	15:40/48	16:40/48
POI 6	10:50/58	11:50/58	12:50/58	14:50/58	15:50/58	16:50/58

A.3 Notes

In order to attain averages at each POI during each of the Cycles, a total of 8 min was spent at each point. This method allowed every POI to be assessed within one hour, with a 2 min breadth to set up the equipment at the subsequent location. At each point, wind speed, ambient temperature and RH values were measured at a height of 1.50m by the KESTEL 4600© every minute for eight minutes.
This technique enabled for average values to be logged by the equipment, and also for the other required data to be obtained. Two other examinations were undertaken with the use of the KKMOON SM206© and the BENETECH GM550©. Firstly, and also at a height of 1.50m, global radiation was measured in order to determine the amount of radiation that was present at each location. Secondly, all paving surfaces were tested in order to define their surface temperature, both in the sun and in the shade.

Appendix B. Mean Physiologically Equivalent Temperature (PET) vs. Physiological Stress (PS) thresholds.

	POI 1		POI 2		POI 3	
	$\overline{PET_{AD}}$	PS	$\overline{PET_{AD}}$	PS	$\overline{PET_{AD}}$	PS
C1	30.0	Moderate Heat Stress	21.5	No Thermal Stress	28.6	Slight Heat Stress
C2	32.6	Moderate Heat Stress	24.0	Slight Heat Stress	32.6	Moderate Heat Stress
C3	34.6	Moderate Heat Stress	29.7	Moderate Heat Stress	33.8	Moderate Heat Stress
C4	30.7	Moderate Heat Stress	34.9	Moderate Heat Stress	37.8	Strong Heat Stress
C5	31.7	Moderate Heat Stress	36.2	Strong Heat Stress	39.4	Strong Heat Stress
C6	29.2	Moderate Heat Stress	37.7	Strong Heat Stress	39.2	Strong Heat Stress

	POI 4		POI 5		POI 6	
	$\overline{PET_{AD}}$	PS	$\overline{PET_{AD}}$	PS	$\overline{PET_{AD}}$	PS
C1	28.2	Slight Heat Stress	30.9	Moderate Heat Stress	26.2	Slight Heat Stress
C2	30.8	Moderate Heat Stress	34.3	Moderate Heat Stress	29.0	Slight Heat Stress
C3	33.8	Moderate Heat Stress	35.8	Strong Heat Stress	28.6	Slight Heat Stress
C4	37.1	Strong Heat Stress	33.0	Moderate Heat Stress	33.4	Moderate Heat Stress
C5	38.2	Strong Heat Stress	32.5	Moderate Heat Stress	33.9	Moderate Heat Stress
C6	37.5	Strong Heat Stress	30.6	Moderate Heat Stress	31.1	Moderate Heat Stress

Key:	$\overline{PET_{AD}}$	PET values for All Days	PS	Physiological Stress
	Colour coded based upon corresponding PS value represented in **Tbl.2**			

Appendix C. SOLUTION DATASHEET Adapted from (Nouri & Costa, 2017b).

C.1	POI 2	POI 3	POI 4	POI 5
Vegetation	x	x		
Shelter Canopies	x		x	
Water / Spray System		x		x

C.2	Vegetation						
	#	PL	Species	Dimensions (*)		Foliation (*)	DeFol. (*)
POI 2	3	LP	Tipuna Tipu	TH : ≈ 12.5m	CD : ≈ 7m	Early May	Mid. March
POI 3	6	GP	Tipuna Tipu	TH : ≈ 12.5m	CD : ≈ 7m	Early May	Mid. March

C.3	Shelter Canopies		
	Material	Watts/m^2 below	Construction/Special Feature
POI 2	Nylon	75	Assembled with cables on tree branches in order to provide shade between tree crowns during the summer (JJA)
POI 4	Aluminium, Acrylic	150	Supported upon a central aluminium structure, seven acrylic flaps are adjustable through a pull-string mechanism which enables the pedestrians to choose to sit in the shade or in the sun in the center of square (JJA)

C.4	Water with surface wetting	LM : RH ≤ 70 % | SMD ≤ 500 μm			
		FP (JJA)	NH	Water Collection	SW Method
POI 3	10:00-11:00	OFF	0m	OFF	OFF
	11:00-12:00	2min + 2min interval		Every 30 min	Surfaces are wet for the specified period and then re-absorbed into the ground slabs
	12:00-13:00	3min + 2min interval			
	14:00-15:00	3min + 1min interval		Every 15 min	
	15:00-16:00	3min + 1min interval			
	16:00-17:00	4min + 1min interval			

C.5	Water without surface wetting	LM : RH ≤ 70 % | T_{amb} > 25 | $\overline{V}$ ≤ 1m/s | $\overline{G_{Rad}}$ < 300 W/m^2			
		PP	NH	SMD	FP (JJA)
POI 5	10:00–11:00	OFF	3 m	OFF	OFF
	11:00–12:00	5.0 $_{Mpa}$		≈ 30 μm	1min + 2min interval
	12:00–13:00	5.5 $_{Mpa}$		≈ 35 μm	2min + 3min interval
	14:00–15:00	5.5 $_{Mpa}$		≈ 40 μm	3min + 2min interval
	15:00–16:00	6 $_{Mpa}$		≈ 40 μm	3min + 2min interval
	16:00–17:00	6 $_{Mpa}$		≈ 45 μm	3min + 1min interval

PL	Planting Layout	TH	Tree Height	LM	Limitation Mechanism	SW	Surface Wetting
LP	Linear Plantation	CD	Crown Dimension	FP	Functioning Period	PP	Pump Pressure
GP	Group Plantation	JJA	June, July, August	NH	Nozzle Height	SMD	Sauter mean diameter

Viñas et al. (1995). El Árbol en Jardinería y Paisajismo - Guía de aplicación para España y países de clima mediterráneo y templado. Barcelona, Spain, Ediciones Omega.

*Dimensions retreived from (Viñas et al. 1995).

References

Akbari, H., Cartalis, C., Kolokotsa, D., Muscio, A., Pisello, A. L., Rossi, F., et al. (2016). Local climate change and urban heat island mitigation techniques − The state of the art. *Journal of Civil Engineering and Management, 22*(1), 1–16.

Alcoforado, M. J., & Andrade, H. (2006). Nocturnal urban heat island in Lisbon (Portugal): Main features and modelling attempts. *Journal of Theoretical and Applied Climatology, 84*, 151–159.

Alcoforado, M. J., & Matzarakis, A. (2010). Planning with urban clmate in different climatic zones. *Geographicalia, 57*, 5–39.

Alcoforado, M. J., Lopes, A., Andrade, H., & Vasconcelos, J. (2005). *Orientações climáticas para o ordenamento em lisboa (relatório 4). Lisboa, C entro de estudos geográficos da universidade de lisboa*.

Alcoforado, M. J., Lopes, A., Andrade, H., Vasconcelos, J., & Vieira, R. (2006). *Observational studies on summer winds in Lisbon (Portugal) and their influence on daytime regional and urban thermal patterns. Merhavim. special issue: climate and environment: Climatological, meteorological and applied aspects tel aviv*. Tel Aviv University88–112.

Alcoforado M.J., H. Andrade, S. Oliveira, (2009). Alterações climáticas e desenvolvimento urbano PoÍtica de Cidades − 4. V. Higgs. Lisboa, D irecção-Geral do Ordenamento do Território e Desenvolvimento Urbano.

Alcoforado, M. J., Lopes, A., Alves, E., & Canário, P. (2014). *Lisbon heat island; Statistical study finisterra, Vol. 98*, 61–80.

Algeciras, J. A. R., & Matzarakis, A. (2017). Quantification of thermal bioclimate for the management of urban design in Mediterranean climate of Barcelona, Spain. *International Journal of Biometeorology, 8*, 1261–1270.

Algeciras, J. A. R., Consuegra, L. G., & Matzarakis, A. (2016). Spatial-temporal study on the effect of urban street configurations on human thermal comfort in the world heritage city of Camagüey-Cuba. *Journal of Building and Environment, 101*, 85–101.

Ali-Toudert, F., & Mayer, H. (2007). Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons. *Journal of Solar Energy, 81*, 725–742.

Almeida, A. L. B. (2006). *The value of trees: The trees and urban forests of Lisbon. Doctoral thesis in landscape architecture*. Superior Institute of Agronomy.

Andrade, H. (2003). *Bioclima humano e Temperatura do ar em Lisboa.* PhD: Universidade de Lisboa.

Beckett, K., Freer-Smith, P., & Taylor, G. (2000). Particulate pollution capture by urban trees: Effect of species and windspeed. *Journal of Global Change Biology,* 995–1003.

Berardi, U. (2016). The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. *Energy and Buildings, 121*, 217–229.

Bourdin, A. (2010). *O urbanismo depois da crise.* Lisbon: Livros Horizonte.

Calheiros, J. (2006). In F. D. P. Santos Miranda (Ed.). *Human health and turism implications. climate change in Portugal. Scenarios, impacts and adaptation measures (SIAM)* (pp. 233–270). Lisbon: Gradiva.

Charalampopoulos, I., Tsiros, I., Chronopoulou-Sereli, A., & Matzarakis, A. (2016). A methodology for the evaluation fo the human-biolcimatic performance of open spaces. *Journal of Theoretical and Applied Climatology,* 1–10.

Coello, A., & Philippe, O. (2015). *Canopia Urbana: Plaça de les glories catalanes − barcelone.* Barcelona, Spain: A gence TER1–36.

Costa, J. P., Sousa, J. F. D., Matos Silva, M., & Nouri, A. S. (2013). Climate change adaptation and urbanism: A developing agenda for Lisbon within the twenty-first century. *Journal of Urban Design International, 19*, 77–91.

Costa, J. P. (2011). *'Climate proof cities'. urbanismo e a adaptação às alterações climáticas. As frentes de água. Lição de agregação em urbanismo apresentada na FA-UTL, Vol. 2*, Lisboa: Universidade Técnica de Lisboa218.

Costa, J. P. (2013). *Urbanism and adaptation to climate change −The waterfronts.* Lisbon, Portugal: Livros Horizonte.

De Abreu-Harbich, L. V., Labaki, L. C., & Matzarakis, A. (2015). Effect of tree planting design and tree species on human thermal comfort in the tropics. *Journal of Landscape and Urban Planning, 138*, 99–109.

Eliasson, I., Knez, I., Westerberg, U., Thorsson, S., & Lindberg, F. (2007). Climate and behaviour in a Nordic city. *Journal of Landscape and Urban Planning, 82*, 72–84.

Erell, E., Pearlmutter, D., & Williamson, T. (2011). *Urban microclimate − Designing the spaces between buildings.* London, United Kingdom: Earthscan.

Fahmy, M., & Sharples, S. (2009). On the development of an urban passive thermal comfort system in Cairo, Egypt. *Journal of Building and Environment, 44*(9), 1907–1916.

Fahmy, M., & Sharples, S. (2011). Urban form, thermal comfort and building CO2 emissions − A numerical analysis in Cairo. *Building Services Engineering Research and Technology, 32*(1), 73–84.

Gómez, F., Cueva, A., Valcuende, M., & Matzarakis, A. (2013). Research in ecological design to enhance comfort in open spaces of a city (Valencia, Spain). Utility of the physiological equivalent temperature (PET). *Journal of Ecological Engineering, 57*, 27–39.

Georgakis, C., & Santamouris, M. (2006). Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes. *Journal of Energy and Buildings, 38*, 367–376.

Höppe, P. (1999). The physiological equivalent temperature − A universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology, 43*, 71–75.

Hwang, R.-L., Lin, T.-P., & Matzarakis, A. (2010). Seasonal effects of urban street shading on long-term outdoor thermal comfort. *Journal of Building and Environment, 46*, 863–870.

IPCC (2000). *IPCC special report emission scenarios, a special report of working group III of the intergovernmental panel on climate change*Cambridge: IPCC27.

IPCC (2013). *Climate change 2013: The physical science basis. working group contribution to the IPCC 5th assessment report. changes to the underlying Scientific/Technical assessment*Cambridge UK: IPCC.

IPCC, (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. R. K. P. a. L. A. M. e. Core Writing Team. Geneva, Switzerland : pp. 151.

Isaac, M., & Vuuren, D. P. V. (2009). Modeling global residential sector energy demand for heating and air conditioning in the contect of climate change. *Energy Policy, 37*, 507–521.

Ishii, T., Tsujimoto, M., & Yamanishi, A. (2008). The experiment at the platform of dry-mist atomization. *Summaries of technical papers of the annual meeting of the Architectural Institute of Japan* (pp. 9). .

Ishii, T., Tsujimoto, M., Yoon, G., & Okumiya, M. (2009). Cooling system with water mist sprayers for mitigation of heat-island. *The seventh international conference on urban climate*.

Ketterer, C., & Matzarakis, A. (2014). Human-biometeorlogical assessment of heat stress reduction by replanning measures in Stuttgart, Germany. *Journal of Landscape and Urban Planning, 122*, 78–88.

Knuijt, M. (2013). *One step beyond. open space, Vol. 85*, Germany: Topos60–67.

Kovats, R., & Ebi, K. (2006). Heatwaves and public health in Europe. *Journal of Public Health, 16*(6), 592–599.

Krüger, E., Drach, P., Emmanuel, R., & Corbella, O. (2013). Assessment of the daytime outdoor comfort levels in and outside the urban area of Glasgow, UK. *International Journal of Biometeorology, 57*, 521–533.

Kuglitsch, F., Toreti, A., Xoplaki, E., Della-Marta, P., & Zerefos, C. (2010). Heat wave changes in the eastern Mediterranean since 1960. *Journal of Geophysical Research Letters, 37*, 1–5.

Lin, T.-P., & Matzarakis, A. (2008). Tourism climate and thermal comfort in sun moon lake, Taiwan. *International Journal of Biometeorology, 52*, 281–290.

Lin, T.-P., Matzarakis, A., & Hwang, R.-L. (2010). Shading effect on long-term outdoor thermal comfort. *Journal of Building and Environment, 45*, 213–221.

Lin, T. (2009). Thermal perception: Adaptation and attendance in a public square in hot and humid regions. *Tzu-Ping Lin, 44*, 2017–2026.

Lopes, A., Alves, E., Alcoforado, M. J., & Machete, R. (2013). Lisbon urban heat island updated: new highlights about the relationships between thermal patterns and wind regimes. *Journal of Advances in Meteorology, 2013*, 1–11.

Lopes, A. (2002). The influcence of the growth of Lisbon on summer wind fields and its environmental implications. *Tyndall/CIB international conference on climate change and the built environment*.

Lopes, A. (2003). *Modificações no clima da lisboa como consequência do crescimento urbano. doctoral thesis.* University of Lisbon.

Matos Silva, M., & Costa, J. P. (2016). Flood adaptation measures applicable in the design of urban public spaces: proposal for a conceptual framework. *Journal of Water, 8*(7), 284.

Matos Silva, M., & Costa, J. P. (2017). Urban flood adaptation through public space retrofits: the case of lisbon (Portugal). *Journal of Sustainability, 9*(5), 30.

Matos Silva, M. (2016). *Public space design for flooding: facing challenges presented by climate change adaptation (Doctoral Degree)*. Universitat de Barcelona.

Matzarakis, A., & Amelung, B. (2008). In M. C. Thomson, R. Garcia-Herrera, & M. Beniston (Eds.). *Physiological Equivalent Temperature as Indicator for Impacts of Climate Change on Thermal Comfort of Humans Seasonal forecasts, climatic change and human health. Advances in global research 30* (pp. 161–172). Berlin: Springer.

Matzarakis, A., & Endler, C. (2010). Climate change and thermal bioclimate in cities: impacts and options for adaptation in Freiburg, Germany. *International Journal of Biometeorology, 54*, 479–483.

Matzarakis, A., & Rutz, F. (2006). Rayman pro – Modelling of mean radiant temperature in urban structures calculation of thermal indices. In A. Matzarakis (Ed.). Germany: Meteorological Institute, Univeristy of Freiburg [Version 2.1 Pro].

Matzarakis, A., Mayer, H., & Iziomon, G. M. (1999). Applications of a universal thermal index: Physiological equivalent temperature. *International Journal of Biometeorology, 42*(2), 76–84.

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments – Application of the RayMan model. *International Journal of Biometeorology, 51*, 323–334.

Matzarakis, A., Fröhlich, D., & Gangwisch, M. (2016). Effect of radiation and wind on thermal comfort in urban environments – Applications of the RayMan and SkyHelios model. *4th international conference on countermeasures to urban heat island*.

Matzarakis, A. (1997). Heat stress in Greece. *International Journal of Biometeorology, 41*, 34–39.

Matzarakis, A. (2016). In T. Karacostas, A. Bais, & P. Nastos (Eds.). *The heat health warning system of DWD – Concept and lessons learned. Perspectives on atmospheroc sciences* (pp. 1259). Switzerland: Springer International Publishing.

Mayer, H., & Höppe, P. (1987). Thermal comfort of man in different urban environments. *Journal of Theoretical and Applied Climatology, 38*, 43–49.

McPherson, E. (1984). In E. McPherson (Ed.). *Planting for solar control. Energy-conserving site design* (pp. 141–164). Washington, D.C: American Soceity of Landscape Architects.

Miranda, P. (2006). In F. Santos, & P. Miranda (Eds.). *The climate in portugal during the XX and XXI centuries climate change in Portugal. Scenarios, impacts and adaptation measures (SIAM)* (pp. 46–113). Lisbon: Gradiva.

Nikolopoulou, M., & Lykoudis, S. (2006). Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Journal of Building and Environment, 41*, 1455–1470.

Nikolopoulou, M. (2007). Use of outdoor spaces and microclimate in a Mediterranean urban area. *Journal of Building and Environment, 42*, 3691–3707.

Nogueira, P., Falcão, J., Contreiras, M., Paixão, E., Brandão, J., & Batista, I. (2005). Mortality in Portugal associated with the heat wave of August 2003: Early estimation

fo effect, using a rapid method. *Eurosurveillance, 10*(7).
Norton, B., Coutts, A., Livesley, S., Harris, R., Hunter, A., & Williams, N. (2015). Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Journal of Landscape and Urban Planning, 134*, 127–138.
Nouri, A. S., & Costa, J. P. (2017a). Placemaking and climate change adaptation: New qualitative and quantitative considerations for the Place Diagram. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability, 10*(3), 1–27.
Nouri, A. S., & Costa, J. P. (2017b). Addressing thermophysiological thresholds and psychological aspects during hot and dry mediterranean summers through public space design: The case of Rossio. *Building and Environment, 118*, 67–90.
Nouri, A. S. (2013). A bottom-up perspective upon climate change – approaches towards the local scale and microclimatic assessment. In H. Bártolo (Ed.). *Green design, materials and manufacturing processes* (pp. 119–124). Lisbon: Taylor & Francis.
Nouri, A. S. (2015). A framework of thermal sensitive urban design benchmarks: potentiating the longevity of auckland's public realm. *Journal of Buildings, 5*, 252–281.
Ochoa de la Torre, J. M. (1999). *Vegetation as an instrument for microclimatic control. Doctoral Degree.* Universitat Politècnica de Catalunya.
Oke, T. (1976). The distinction between canopy and boundary layer urban heat islands. *Journal of Atmosphere, 14*, 268–277.
Oke, T. (1988). The urban energy balance. *Journal of Progress in Physical Geography, 12*, 38.
Oliveira, S., & Andrade, H. (2007). An initial assessment of the bioclimatic comfort in an outdoor public space in Lisbon. *International Journal of Biometeorology (52 − Climate and Perception),* 69–84.
Oliveira, S., Andrade, H., & Vaz, T. (2011). The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in Lisbon. *Journal of Building and Environment, 46*, 2186–2194.
Picot, X. (2004). Thermal comfort in urban spaces: Impact of vegetation growth. Case study: piazza della Scienza, Milan, Italy. *Journal of Energy and Buildings, 36*, 329–334.
Qiu, G.-Y., Li, H.-Y., Zhang, Q.-T., Chen, W., Liang, X.-J., & Li, X.-Z. (2013). Effects of Evapotranspiration on Mitigation of Urban Temperature by Vegetation and Urban Agriculture. *Journal of Integrative Agriculture, 12*(8), 1307–1315.
Rogelj, J., Meinshausen, M., & Knutti, R. (2012). Global warming under old and new scenarios using IPCC climate sensitivty range estimates. *Nature and Climate Change,* 1–6.
Santamouris, M., Gaitani, N., Spanou, A., Salirai, M., Giannopoulou, K., Vasilakopoulou, K., et al. (2012). Using cool paving materials to improve microclimate of urban areas − Design realization and results of the flisvos project. *Journal Building and Environment, 53*, 128–136.
Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., Prasad, D., & Synnefa, A. (2016). Passive and active cooling for the built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data form 220 large scale projects. *Solar Energy, 154*, 14–33.
Santamouris, M. (2007). Heat island research in europe: The state of the art advances in building energy research. *Advances in Building Energy Research, 1*, 123–150.
Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat islands − A review of the actual developments. *Journal of Renewable and Sustainable Energy Reviews, 26*, 224–240.
Santos, F. D., & Miranda, P. (2006). *Alterações climáticas em Portugal. cenários, impactos e medidas de adaptação – projecto SIAM II*.
Shashua-Bar, L., & Hoffman, M. (2000). Vegetation as a climatic component in the design of an urban street; An empirical model for predicting the cooling effect of urban green areas with trees. *Journal of Energy and Buildings, 31*, 221–235.
Shashua-Bar, L., Potchter, O., Bitan, A., Boltansky, D., & Yaakov, Y. (2010). Microclimate modelling of street tree species effects within the varied urban morphology in the Mediterranean city of Tel Aviv, Israel. *International Journal of Climatology, 30*, 44–57.
Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2011). The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *International Journal of Climatology, 31*, 1498–1506.
Shashua-Bar, L., Tsiros, I. X., & Hoffman, M. (2012). Passive cooling design options to ameliorate thermal comfort in urban streets of a Mediterranean climate (Athens) under hot summer conditions. *Journal of Building and Environment, 57*, 110–119.
Stathopoulou, M., Synnefa, A., Cartalis, C., Santamouris, M., Karlessi, T., & Akbari, H. (2009). A surface heat island study of Athens using high-resolution satellite imagery and measurements of the optical and thermal properties of commonly used building and paving materials. *Journal of Sustainable Energy, 28*, 59–76.
TVK (2013). *Place de la republique. TVK./Press kit – place de la republique.* Paris: Trevelo & Viger-Kohler Architectes Urbanistes21.
Taha, H., Akbari, H., & Rosenfeld, A. (1988). *Vegetation canopy micro-climate: A field project in Davis, California Laboratory Report-24593*Berkley, California: Lawrence Berkeley Laboratory, University of California.
Takács, A., Kiss, M., Hof, A., Tanács, E., Á. Gulyás, & Kántor, N. (2016). Microclimate modification by ubran shade Trees – An integrated approach to aid ecosystem service based decision making. *Journal of Environmental Sciences, 32*, 97–109.
Tan, Z., Lau, K. K.-L., & Ng, E. (2016). Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. *Journal of Energy and Buildings, 114*, 265–274.
Tsiros, I. (2010). Assessment and energy implications of street air temperature cooling by shade trees in Athens (Greece) under extremely hot weather conditions. *Journal of Renewable Energy, 35*, 1866–1869.
Vanos, J., Warland, J., Gillespie, T., & Kenny, N. (2010). Review of the physiology of human thermal comfort while exercising in urban landscapes and implications for bioclimatic design. *International Journal of Biometeorology, 54*.
Viñas, F., Solanich, J., Vilardaga, X., & Montilo, L. (1995). *El Árbol en Jardinería y Paisajismo − Guía de aplicación para España y países de clima mediterráneo y templado Barcelona.* Spain: Ediciones Omega.
Walton, D., Dravitzki, V., & Donn, M. (2007). The relative influence of wind: Sunlight and temepratures on used comfort in urban outdoor spaces. *Journal of Building and Environment, 42*, 3166–3175.
Wang, Y., Berardi, U., & Akbari, H. (2016). Comparing the effects of urban heat island mitigation strategies for Toronto. *Canada. Energy and Buildings, 114*, 2–19.
Wilbanks, T. J., & Kates, R. W. (1999). Global change in local places: How scale matters. *Climatic Change, 43*, 601–628 [The Netherlands].